

Fire Behavior and Energy Observational Plan

1. Overview

The Fire Behavior and Energy (FBE) discipline, in collaboration with operations and other measurement and modeling disciplines, will focus on answering key science questions related to the character and spatial organization of the “handoff” of mass and energy between the fire and plume. The characteristics of the handoff is inherently a question of how the fire environment, ignition operations, and coupled fire-atmosphere behavior interact across spatial scales. The FBE discipline will also provide specified heat source and emissions data across burn units required for model input and evaluation. Achieving these goals will require a combination of remote sensing, coordinated in situ measurements, and modeling. Not only must the FBE team coordinate with other FASMEE disciplines, but should provide continuity with ongoing projects that focus on fine-scale combustion (e.g., Strategic Environmental Research and Development Program (SERDP) projects), regional-scale smoke (Fire Influence on Regional and Global Environments Experiment (FIREX)/Fire Impacts on Regional Emissions and Chemistry (FIREChem)), and other areas of fire science (e.g., EcoFASMEE) to make best use of FASMEE data.

The active-fire measurements described below include a mix of ground- and tower-based and remotely-sensed measurements (Figures 1 and 2). The relevant measurement scales in order of extent include flame front (~1-10 m), interacting flame fronts, plume core, and unit. Remotely-sensed measurements will involve both polar orbiting and geosynchronous satellites and airborne platforms. The polar orbiting satellite measurements will require, as possible, coordination with operations on the timing of ignition.

Two forms of airborne sampling will likely be required to obtain both quantitative fire radiation measurements and fire spread data at high temporal frequency. Quantitative imagery from a nadir perspective should be collected every 3-5 minutes with an effective spatial resolution of ≤ 10 m. Fire spread information is needed at higher frequency (≤ 1 min) and higher spatial resolution (≤ 5 m). Given currently available sensors and platforms, FBE sampling flights lines

are expected to be performed 5,000 to 10,000 ft above ground pending de-conflicting arrangements with other airborne systems being used (e.g., airborne fire line ignition) or proposed (e.g., airborne smoke sampling). Piloted airborne sampling systems should be prioritized unless a viable plan for using unmanned aerial systems (UAS) to obtain these measurements is proposed.

Extensive work in the burn units in the days leading up to each prescribed fire will be required to install ground- and tower-based equipment that will characterize fires at fine-scale. Access to the burn unit on the day of the fire will likely be required to launch equipment. Equipment retrieval will be required after the fires while, at the same time, safety risks must be mitigated. In high-intensity stand-replacement fires, the harsh ambient conditions will likely prohibit overhead, ground-leaving, and quantitative flame-front radiation measurements from imaging instruments on towers at each distributed measurement location in Figure 1 (i.e., ground/tower locations). Alternatively, oblique imaging may be accomplished from tall towers erected adjacent to burn units.

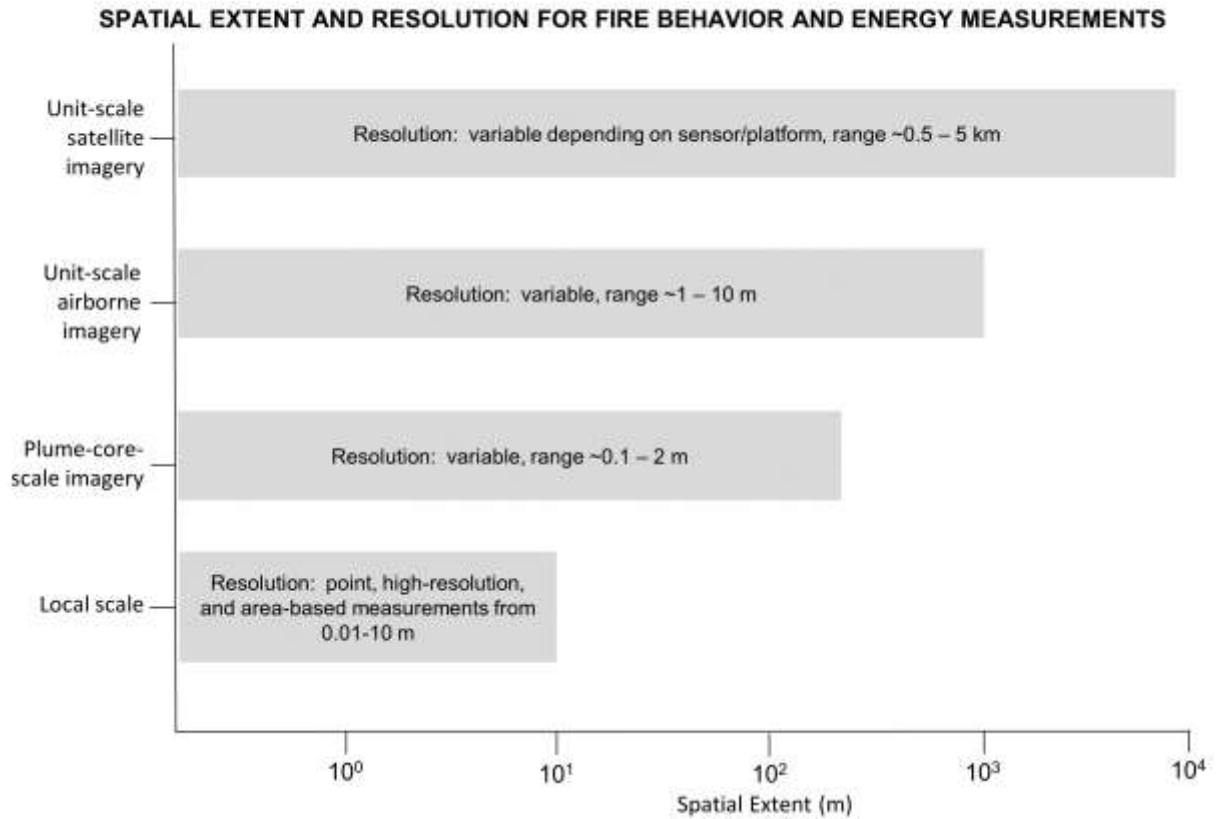


Figure 1: Hierarchical sampling scales of fire behavior and energy measurements. The satellite and airborne fire radiation measurements will occur at unit extents. Plume-core-scale imagery will occur at high temporal frequencies but at moderate extents similar to plume-core structures. The coordinated fire dynamics and emissions measurements will involve local (point and flame-front) scale measurements from ground and towers.

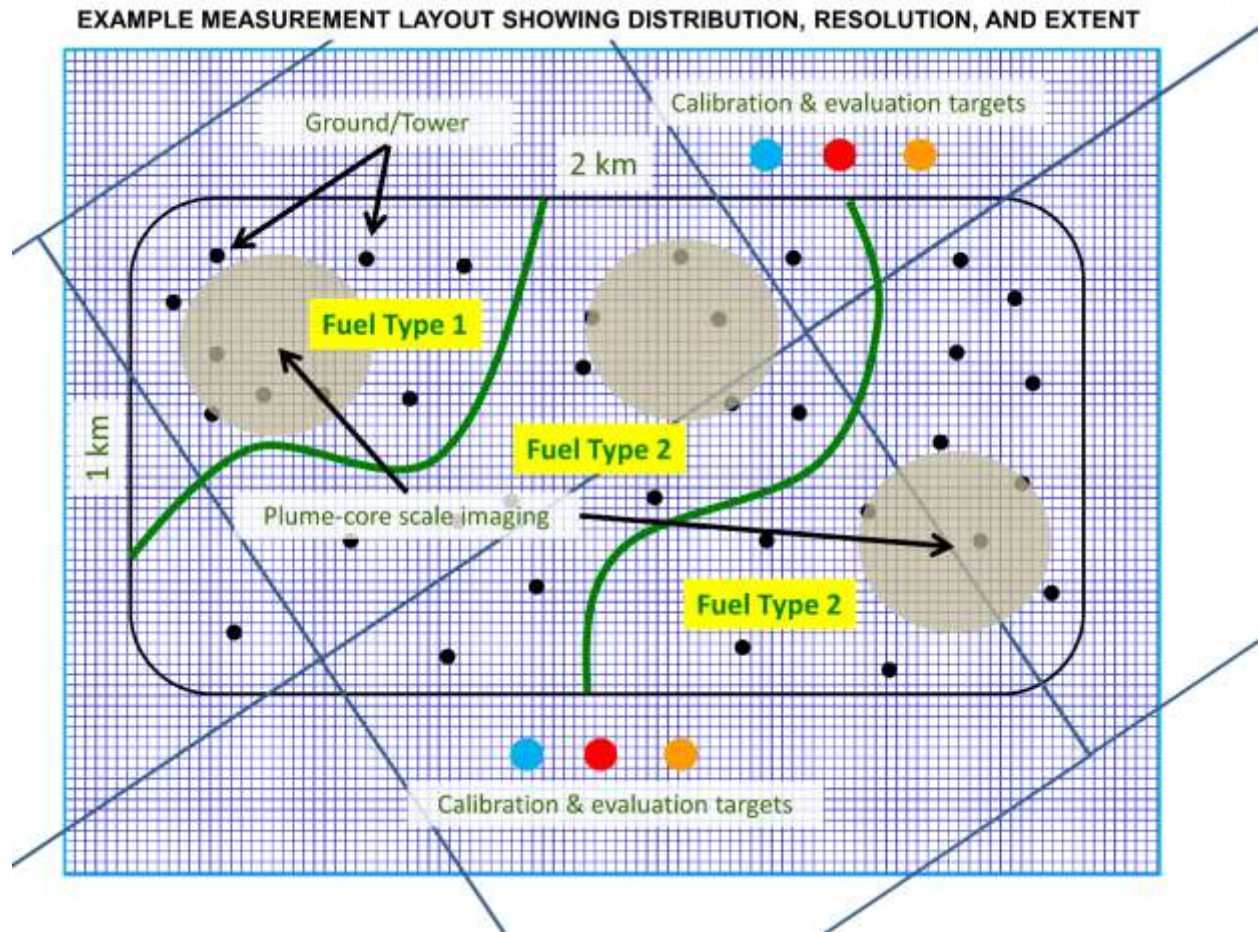


Figure 2: An example spatial overlay of satellite (large) and airborne measurement grids (small) covering the full extent of burn units. Calibration and evaluation targets should be used to improve airborne infrared radiation measurements. Within burn units, coordinated measurements must be distributed in a stratified manner by fuel type and, as possible, expected fire behavior (e.g., heading vs flanking and surface vs crown fire). Imagery collected at high temporal frequency and spatial resolution and moderate spatial extent (coinciding with expected plume core development) should, in combination with flame-front-scale and unit-scale imagery, be used to examine the genesis and evolution of plume cores.

2. Fire Behavior and Energy Subtasks

The central measurement challenges for FASMEE's Fire Behavior and Energy discipline are to 1) characterize spatially-resolved and multi-scale Fire Radiative Flux Density (FRFD) across burn units (the radiation field), 2) describe the fire's heat and mass budgets across their range in variability, and 3) use these measurements and analyses to derive spatially and temporally-resolved inputs needed by plume and smoke chemistry models. Coordinated measurements (e.g.,

Hudak et al. 2016, Butler *et al.* 2016, Dickinson et al. 2016, O'Brien *et al.* 2016), including fuel consumption; emissions partitioning between flaming and post-frontal combustion; and flame front dimensions, dynamics, and energy transfer must be conducted hierarchically across their expected range of variability within and among fires. Fire imagery must be collected in a nested design (spanning spatiotemporal scales) in order to characterize plume genesis and evolution from local flame-fronts to interacting flame fronts and from interacting flame fronts to plume cores.

Specific subtasks for this discipline are organized by the spatial scale of their regard and, by necessity, combine measurement and modeling:

- Unit-scale remotely-sensed fire radiation
- Plume-core-scale remotely-sensed fire radiation
- Coordinated fire dynamics and emissions measurements at local (flame-front) scales

The unit-scale remotely-sensed fire radiation measurements must encompass the spatial extent of burn units (Figure 1). Plume-core-scale imagery should be of sufficient temporal frequency and spatial resolution and extent to capture the organization of fire heat release. Modeling is required to correct for potential canopy interception for surface fires. The local, coordinated fire dynamics and emissions measurements must combine ground and tower-borne instruments and will be a combination of point measurements, often replicated vertically (e.g., convective and emission fluxes), and area-based measurements (radiometry, fire imaging). Plume model input datasets should be developed through data integration and reduction.

3. Fire Behavior and Energy Identified Observations

In Table 1, we describe the suite of measurements and modeling tasks proposed for the Fire Behavior and Energy discipline. Recommended modeling tasks are included in order to provide the required input data content and format for plume and smoke chemistry modelers. Modeling tasks should include 1) simulation of potential radiation interception by forest canopies that intervene between fires and airborne and satellite sensors and 2) specification of stationary burners in a hydrodynamic code that simulate flame front heat generation and provide inputs to

plume models. Other modeling exercises may be required to support the measurement process, including, potentially, 1) coupled-fire atmosphere simulations that would help identify the relevant spatial and temporal scales for the organization of plume cores and 2) modeling that would help characterize flame fronts and energy transfer from limited measurements. Because of flame energy and size, certain modifications of the measurement plan for crown fires will be needed and must be detailed. For crown-fire flames, unit-scale, quantitative airborne radiation imagery (rather than tower-based measurements) may be sufficient for fire characterization at distributed measurement locations, though interpolation will generally be required because of limits on airborne sampling rates. Measurements replicated vertically on towers will generally only describe gradients part-way through the length of crown-fire flames. As such, extrapolation will be needed to fully characterize flames and lower plume conditions. Extrapolation may be facilitated by measurement modification and modeling, particularly for variables such as flame-front dimensions and spread rates, flame energy transport, emissions fluxes, combustion efficiency, and the partitioning of flaming and smoldering combustion.

Table 1: Observational specifications for the Fire Behavior and Energy discipline.

MEASUREMENT	SPATIOTEMPORAL SCALES	OBSERVATION (MINIMUM)	ADDITIONAL SPECIFICATIONS
Unit-scale remotely-sensed fire radiation			
<i>Satellite active fire observation</i>			
Quantitative fire radiation from polar-orbiting satellites	<ul style="list-style-type: none"> • Spatial extent – whole burn unit • Time scale - single observation during burning period 	<ul style="list-style-type: none"> • Fire radiative power 	<ul style="list-style-type: none"> • Provide details on schedule, image specifications, and methods • Evaluate against airborne data • Coordinate with other projects (e.g., FIREChem), measurement teams, and operations
Quantitative fire radiation from geosynchronous satellites	<ul style="list-style-type: none"> • Spatial extent – entire burn unit • Time scale – multiple observations during burning period 	<ul style="list-style-type: none"> • Fire radiative power & energy 	<ul style="list-style-type: none"> • Provide details on image specifications and methods • Evaluate against airborne data • Coordinate with other projects (e.g., FIREX/FIREChem), measurement teams, and operations
<i>Airborne active fire observation and modeling</i>			
Unit-scale quantitative fire radiation	<ul style="list-style-type: none"> • Spatial extent – entire burn units • Spatial resolution ≤ 10 m • Imaging interval ≤ 5 min over entire burning period (3-7 hours) 	<ul style="list-style-type: none"> • Fire radiative power & energy • Emissivity-area product • Spotting density and distance • Visible imagery 	<ul style="list-style-type: none"> • Compare with ground evaluation data and calibrate as needed • Detail camera specifications and operation including performance at background and high power • Contingency plan relative to Mid-Wave Infrared (MWIR) saturation • Provide refueling/rest plan • Coordinate with other measurement teams and operations
Canopy interception correction for surface fires	<ul style="list-style-type: none"> • Same as for unit-scale quantitative fire radiation 	<ul style="list-style-type: none"> • Fraction of fire radiative power & energy intercepted by canopy per pixel 	<ul style="list-style-type: none"> • Ray tracing approach preferred • Use canopy data to derive parameters • Assess error from canopy heat interception and (re)radiation
Ground calibration and evaluation targets	<ul style="list-style-type: none"> • Spatial extent – subpixel to multiple airborne pixels • Spatial resolution – subpixel to multiple airborne pixel • Time scale – entire burning period (3-7 hrs) 	<ul style="list-style-type: none"> • Fire radiative power and energy • Combustion total and rate where applicable • Emissivity and area data 	<ul style="list-style-type: none"> • Replicated cold (e.g., water bodies), background, and hot (e.g., fire) targets • Provide adequate airborne data fire retrieval error characterization • Coordinate with other measurement teams and operations

Unit-scale fire spread	<ul style="list-style-type: none"> • Spatial extent – entire burn unit • Spatial resolution ≤ 5 m • Imaging interval ≤ 1 min over entire burning period (3-7 hrs) 	<ul style="list-style-type: none"> • High quality infrared imagery, visible as a supplement if possible • Fire spread mapping across unit and through burning period 	<ul style="list-style-type: none"> • Develop algorithm for seamless calculating fire spread rates • Provide refueling/rest plan • Coordinate with other measurement teams and operations
Distributed & coordinated fire dynamics and emissions			
Plume-core scale quantitative fire radiation	<ul style="list-style-type: none"> • Spatial extent ~ 100 m • Spatial resolution – sub-flame front • Time scale >0.5 Hz 	<ul style="list-style-type: none"> • Fire radiative power & energy 	<ul style="list-style-type: none"> • Intent is to provide moderate scale imagery that links the local and unit scales relative to fire spatial structure
Overhead, ground-leaving, flame-front radiation	<ul style="list-style-type: none"> • Spatial extent – locations distributed across burn units • Spatial resolution – flame front • Time scale > 0.5 Hz 	<ul style="list-style-type: none"> • Fire radiative power & energy from flame front • Estimate fire fractional area and flame-front emissivity 	<ul style="list-style-type: none"> • Match units/specifications of airborne quantitative data • Develop correlations with flame front characteristics and energy transport • Coordinate with other measurement and modeling • These measurements have been made from towers in the past and will likely not be possible in high-intensity fires
Flame-front dimensions and spread rates	<ul style="list-style-type: none"> • Spatial extent – locations distributed across burn unit • Spatial resolution – flame front • Time scale ≥ 1 Hz 	<ul style="list-style-type: none"> • Flame front spread rate • Flame residence time • Flame dimensions • Spatial variation 	<ul style="list-style-type: none"> • Methods to include imaging • Consider 3D models from multi-perspective imagery • Coordinate with other measurements and modeling
Flame energy transport	<ul style="list-style-type: none"> • Spatial extent – locations distributed across burn units • Spatial resolution – flame front • Time scale ≥ 10 Hz 	<ul style="list-style-type: none"> • Flame “exit” convective flux (velocity & gas temperature) • Flame-front radiative flux • Soil heat flux 	<ul style="list-style-type: none"> • Measurement units/specifications for radiative flux comparable to overhead, ground-leaving flame-front radiation • Multi-height measurements expected for convective flux • Coordinate with other measurements and modeling, esp. to constrain fire heat and emissions budget
Emissions fluxes and combustion efficiency	<ul style="list-style-type: none"> • Spatial extent – sample locations distributed across burn units • Spatial resolution – point measurements at multiple heights • Time scale ≥ 1 Hz 	<ul style="list-style-type: none"> • Convective flux • Latent heat flux • CO & CO₂ fluxes and combustion efficiency • Particulate emissions 	<ul style="list-style-type: none"> • Multi-height measurements to provide vertical gradient through flame and lower plume (i.e., source term after combustion reactions are complete). • Monitor the evolution of the combustion process from flaming to smoldering phases • Coordinate with other measurements and modeling,

			esp. to constrain fire heat and emissions budget
Partitioning flaming & smoldering combustion	<ul style="list-style-type: none"> • Spatial extent – sample locations distributed across burn units • Spatial resolution – flame front • Time scale ≥ 1 Hz 	<ul style="list-style-type: none"> • Partition flaming and smoldering consumption • Flaming and smoldering contribution to fire energy 	<ul style="list-style-type: none"> • Consider image analysis methods • Relate to emissions fluxes and combustion efficiency • Coordinate with other measurements and modeling, esp. to constrain fire heat and emissions budget
Data integration			
Burner method for integrating fuels, fire behavior and energy, and meteorology to provide input data to plume models (see associated Study Plan Appendix)	<ul style="list-style-type: none"> • Spatial extent – whole burn unit • Spatial resolution – flame front • Time scale ≤ 1 Hz 	<ul style="list-style-type: none"> • Gas temperature, velocity, and convective flux at flame “exit” • Vertical mixing to lowest level of plume model 	<ul style="list-style-type: none"> • Burners modeled within hydrodynamic code • Canopy attenuation of energy included for surface fires under forest canopy • Coordinate with measurement disciplines

4. Fire Behavior and Energy Measurement Justification

The coordinated fire and emissions measurements and modeling in Table 1 form a set of activities that will allow FASMEE to answer key science questions and provide convective flux data to plume modelers and high quality emissions information to smoke chemistry modelers. Fire behavior and energy, in concert with fuels and meteorology, determine the heat source for plume rise. The spatial organization of that heat release has been shown to be an important determinant of plume dynamics and the fates of smoke (Actemeier et al. 2012). Cross-scale measurements of fire radiation (from fuel cells [Hiers et al. 2009], to interacting flame fronts, to plume cores [Liu et al. 2010]) should allow the FASMEE science team to answer questions about the genesis and evolution of spatial structure in plumes (see Science Questions) and form the foundation from which convective and emissions fluxes are inferred.

Radiation from fires measured from airborne platforms is the only fire behavior and energy measurement that can be accomplished at high spatial and temporal resolution and at landscape extents (Riggan et al. 2004, Schroeder et al. 2013, Dickinson et al. 2016). As such, radiation mapping, along with spatial fuel maps, will be foundational to the spatial understanding of fire and plume development and to the success of FASMEE. However, such measurements require extensive assumptions regarding the energy source, the atmosphere, canopy, and other attributes, which leads to considerable measurement uncertainty. The airborne measurements, ground

evaluation (i.e., “truthing”), and associated modeling processes presented in Table 1 describe a suite of activities intended to reduce uncertainty and provide the highest quality fire radiation mapping possible. Based on currently available options, one airborne sensor should provide quantitative, nadir (overhead) measurements of fire radiative flux density while a second sensor should be required to provide high frequency measurement for mapping flame front spread rates. The measurement process will include radiation targets (cold, ambient, and hot) that will permit airborne measurement evaluation and, if needed, provide ground-calibration sources (Figure 2). Measurement requires estimates of fire radiation attenuation when surface fires burn below a forest canopy (Hudak et al. 2016, Mathews et al. 2016) and, with canopy characteristics provided by the Fuels and Consumption discipline, established software can be used to model canopy radiation transmission and interception (e.g., CESBIO 2016, DIRSIG 2016). FASMEE airborne radiation measurements, particularly with additional rapid response opportunities (e.g., FIREX /FIREChem), will also advance the goal of satellite measurement evaluation, critical for widespread application of FASMEE science to smoke management (Peterson et al. 2013, Schroeder et al. 2013, Dickinson et al. 2016).

Fire radiation fields form the foundation from which convective and emission fields are inferred. Fire convective and emission fields are required as inputs to plume models and as data to evaluate those models. In order to produce convective and emissions fields from fire radiation, coordinated ground-based measurements of key components of fire heat budgets are required. Coordinated measurements are expected to be distributed across burn units so as to capture variability in fuels and fire behavior (Figure 6). Two main organizing themes motivate fire behavior and energy measurements and integration with other measurement disciplines. First, in a central data integration step (see Table 1, data integration), a subset of measurements should be used to parameterize stationary flame-like vents (“burners”) in a hydrodynamic model (see Study Plan - Smoke Plume Model Development Using Burner Method) to provide spatial heat-source inputs to plume models). Development of a consistent and well-founded input dataset will facilitate the use of FASMEE results to evaluate and compare a suite of plume models for both surface and crown fires. Second, the quantity and quality of emissions from fires is fundamentally determined by the fire’s heat and mass budget that integrates fuel consumption, partitioning of emissions between flame front and post-frontal combustion, combustion

efficiency, and energy sinks and dissipation modes (e.g., Kremens et al. 2012). Coordinated in-fire and near-source measurements should be used to constrain the heat and mass budget across a wide range of variability in fuels and fire behavior. Results will provide smoke chemistry modelers with information allowing them to assess model assumptions relative to source emissions across flaming and smoldering regimes. Crown fires, because of large flame size and heat emission, impose constraints on in-situ (point and flame-front scale) measurements and we expect that modification of measurement methods and, potentially, flame front modeling will be needed to provide flame “exit” estimates of key variables such as convective fluxes.

5. Citations

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